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Title:	Fermi Guest Investigator Program Cycle 2 Project Final Report Albedo Polarimetry of Gamma-Ray Bursts and Solar Flares with GBM
Author(s):	Kippen, Richard Marc
Intended for:	Final report to sponsor Report

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Albedo Polarimetry of Gamma-Ray Bursts and Solar Flares with GBM

Author(s): R. Marc Kippen (LANL)

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Fermi Guest Investigator Program Cycle 2 Project Final Report

Albedo Polarimetry of Gamma-Ray Bursts and Solar Flares with GBM

R. Marc Kippen (LANL)

Project Abstract

Several key properties of GRBs remain poorly understood and are difficult or even impossible to infer with the information currently being collected. Polarization measurements will probe the precise nature of the central engine. For solar flares, high-energy polarization measurements are expected to be useful in determining the beaming (or directivity) of solar flare electrons—a quantity that may provide important clues about electron acceleration and transport. We propose to investigate the viability of using the *Fermi* Gamma-ray Burst Monitor (GBM) to measure the polarization of GRBs and solar flares using the albedo photon flux. This approach was previously developed for use with BATSE data. We will conduct a careful study of this technique using a modified version of the GRESS simulation tools developed by the GBM team.

Project Final Report

This project was mainly executed by the Principal Investigator Dr. Mark McConnell of the University of New Hampshire (UNH). The final report from UNH included in the Appendix describes the main technical results.

The LANL role in this project was to support Dr. McConnell in the use and modification of the required General Response Simulation System (GRESS). The amount of support actually required was small. Upon initial interactions it was clear that the most efficient path was for Dr. McConnell to implement the needed changes himself. Following brief discussions and orientation from LANL, he was able to quickly and efficiently understand, modify, and use GRESS to include the polarization physics needed for this project. Results are described in the Appendix. Remaining involvement of LANL was to maintain the GRESS code for compatibility with underlying packages, tasks covered by direct support from the GBM team.

Appendix

Copy of project final report from the PI institution: McConnell, M. L., "Final Technical Report Albedo Polarimetry of Gamma-Ray Bursts and Solar Flares with GBM."

Final Technical Report

Albedo Polarimetry of Gamma-Ray Bursts and Solar Flares with GBM

NASA Grant NNX10AE49G

UNH Project Id 143312

Period of Performance:
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(including 1-year no-cost extension)

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Overview

In spite of extensive observational efforts (e.g., CGRO, HETE-2, BeppoSAX, INTEGRAL, Swift, and others), several key properties of GRBs remain poorly understood and are difficult or even impossible to infer with the spectral and lightcurve information currently collected. Polarization measurements will lead to unambiguous answers to many open questions. A detailed polarization study of prompt GRB emission is the only possible means of probing the structure of the central engine, the region closest to the nascent black hole. In particular, polarization observations of GRBs can address issues related to the geometric and magnetic structure of the inner engine and also provide clues as to the nature of the processes responsible for the γ-ray emission (e.g., Lazzati 2006; Toma et al. 2009).

Polarization results for GRBs are quite limited. Coburn and Boggs (2003) reported the first positive GRB polarization measurement. They found a polarization level of ~80% in GRB021206 using data from RHESSI, although this result has been met with considerable skepticism (e.g., Wigger et al. 2004; Rutledge & Fox 2004). Willis et al. (2005) claimed polarization levels of >35% and >50% from GRB930131 and GRB960924 using an albedo polarization analysis of BATSE data. Finally, McGlynn et al. (2007) reported a possible (2σ) detection of polarization (at a level of ~60%) from GRB041219a using INTEGRAL/SPI imaging data, although systematic effects could not be ruled out. (Kalemci et al (2007) reported a polarization level of 98% ±33% from the same data set.) Although these results are far from conclusive, they do suggest rather large levels of GRB polarization.

For solar flares, high-energy polarization measurements are expected to be useful in determining the beaming (or directivity) of solar flare electrons, a quantity that may provide important clues about electron acceleration and transport. Measurements at energies above ~50-100 keV are expected to be most useful (Chanan et al. 1988), where we expect large linear polarizations of the electron bremsstrahlung radiation due to the anisotropy of the electrons (e.g., Bai & Ramaty, 1978; Leach and Petrosian, 1983). Data from the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) have been used, using different analysis methods, to search for polarization from solar flares at energies up to 100 keV (McConnell et al. 2002, 2003a, 2003b) and at energies above 150 keV (Boggs et al. 2006; Suarez-Garcia et al. 2006). Unfortunately, none of the RHESSI results published so far provide unambiguous evidence for polarization. Zhitnik et al. (2006) reported the detection of hard X-rays from more than 90 flares using a polarimeter on the Coronas-F spacecraft, only one of which showed significant levels of polarization, at levels in excess of 50%. Upper limits for 25 other events were in the range of 8% to 40%. Additional data will be needed for further progress to be made.

We proposed to investigate the viability of using GBM to measure the polarization of GRBs and solar flares using the albedo photon flux. This approach was previously developed for use with BATSE data (McConnell et al. 1996a, 1996b; Willis et al. 2005). Although the GBM detectors have a much smaller effective area than that of BATSE, the sensitivity of this technique also depends on the directional nature of the detector response, for which the GBM detectors may have more of an advantage due to the larger number and arrangement of the detectors. We proposed to conduct a careful study of this technique using a modified version of the GRESS (General Response Simulation Software) simulation tools developed by the GBM team, a development effort that was led by our LANL collaborator Marc Kippen.

Earth Albedo Polarimetry

A useful aspect of both Compton and Rayleigh scattering is that scattered photons tend to be scattered at right angles with respect to the electric field vector of the incident photon. Polarimetry techniques for energies from ~1 keV up to several MeV rely on this important property. Albedo polarimetry is no exception. In the case of an unpolarized beam of incident photons, there will be no preferred azimuthal scattering angle. However, in the polarized case, the incident photons will exhibit an asymmetric distribution. A spherical body (such as the Earth) irradiated by a radiation source presents a wide range of possible scatter angles for a given source direction. As a result, the intensity distribution of the albedo flux will exhibit an angular distribution that will depend on the polarization properties of the source radiation. It is this feature of the albedo flux that can be exploited for the purpose of measuring polarization. The scattered photon spectrum is modified from its original form by inelastic (Compton) scattering, but the original spectrum can be reconstructed from the scattering geometry. In the same way, with sufficient statistics, the energy-dependence of the polarization can also be reconstructed.

For the case of a detector in Earth orbit observing flux scattered off the Earth's atmosphere, the distribution of the scattered albedo flux across the top of the atmosphere will depend on three parameters: 1) the angular height of the source above the Earth's limb; 2) the level of linear polarization of the source flux; and 3) the orientation of the bulk polarization vector of the source flux. Therefore, if one knows the direction of the source, then the polarization properties can be determined from a study of the albedo flux. We had previously modeled this scattering process off the Earth's atmosphere using Monte Carlo simulations, incorporating a version of GEANT3 which has been modified to handle polarized photons using the GLEPS (GEANT3 Low Energy Polarized Scattering) package (McConnell et al. 2009). The goal of that original work was to use data from CGRO/BATSE in an effort to study the polarization of gamma-ray bursts and solar flares using observations of the scattered albedo flux.

The BATSE instrument on CGRO (Fishman et al. 1994) consisted of an array of eight large-area scintillation detectors, one at each corner of the CGRO spacecraft. Each (un-collimated) detector was sensitive to flux within a solid angle of roughly 2π steradian. Simulations showed that differences in the detector count rates (for those detectors directed towards the Earth), could be used to determine source polarization. For the largest GRBs, the minimum detectable polarization (MDP) was found to be as low as ~20% (McConnell et al. 1996b), much lower than the ~80% polarization level reported by Coburn and Boggs (2003). The analysis of the BATSE albedo data was hampered by the lack of a high-fidelity simulation of not only the BATSE instrument itself, but also the CGRO spacecraft. Willis et al. (2005) included a crude model of the spacecraft in their analysis, which led to the first evidence for polarization from a study of the albedo flux. For GBM, we already have a high-fidelity mass model incorporated into the GRESS simulation package that encompasses not only the GBM detectors, but also the entire Fermi spacecraft. This greatly facilitates our development of this approach for GBM.

GRESS Simulations

GRESS is a software system for modeling and simulating the physical and instrumental response of high-energy radiation detection systems (Hoover et al. 2008; Bissaldi et al. 2009). It is primarily designed to account for the effects of radiation interactions in the detectors and their surrounding materials (e.g., spacecraft, mounting structures, Earth, etc.). The system is composed of several application programs distributed as an integrated package. The main simulation applications are based on the GEANT4 Monte Carlo simulation package from CERN. GRESS was originally developed to support the GBM, but is generally applicable to a wide range of other space- and ground-based instrument systems. Experimental data from extensive GBM calibrations with radioactive sources were used to validate GRESS.

We successfully modified the existing GRESS program to include the effects of polarized photons in both Compton and Rayleigh scattering processes. With these modifications, we have used GRESS to simulate some of the characteristics of the polarized albedo flux. The results are generally consistent with results we had generated several years ago with GEANT3 simulations.

First we completed a series of mono-energetic runs, each with 10 million incident photons uniformly illuminating the Earth with a plane-parallel beam. The fraction of photons that are scattered by the atmosphere at various energies is shown in Figure 1. In the range of 100 up to several hundred keV, roughly 40% of the incident flux scatters off the atmosphere.

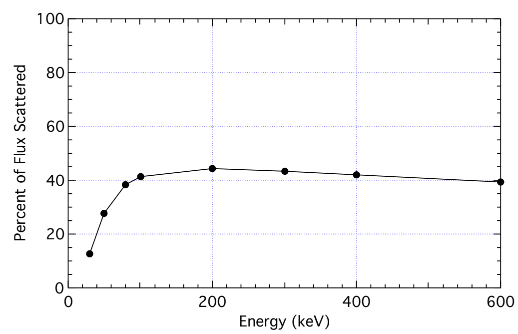

Figure 1. Fraction of flux scattered off the atmosphere as a function of incident photon energy.

The photons are scattered off the atmosphere with a loss of energy. Some of the resulting energy loss spectra (again, for a mono-energetic incident photon beam) are shown in Figures 2-5.

The results for the spatial distributions in each energy (for both polarized and unpolarized incident beams) are shown in Figures 6-11. These diagrams show the observed angular distribution of scattered photons across the disk of the Earth for a source that is directly overhead (at the local zenith). Note the different scales in each case. The direction of polarization of the incident beam is in the vertical direction. The asymmetry that results from the polarized case represents a signature that can, in principle, be used to infer the polarization (both magnitude and direction) of the incident beam. As a measure of the magnitude of this asymmetry, we defined a modulation factor based on the maximum and minimum points at the geo-center angle where the asymmetry is most pronounced. Estimates based on the these plots have been used to generate the data in Figure 12, which shows this modulation factor as a function of incident photon energy. Clearly, the polarization signature is most pronounced at low incident photon energies.

For a typical power law distribution of photons, most of the scattered flux comes out at energies between 10 and 50 keV. Figures 13 to 15 show the spectrum of scattered photons for power law spectra with photon spectral indices of -2.0, -2.5 and -3.0, respectively. A harder incident spectrum results in a scattered spectrum with somewhat higher peak energy. These examples (which span a range of typical spectral indices for gamma-ray bursts and solar flares) all have most of their scattered flux below 50 keV.

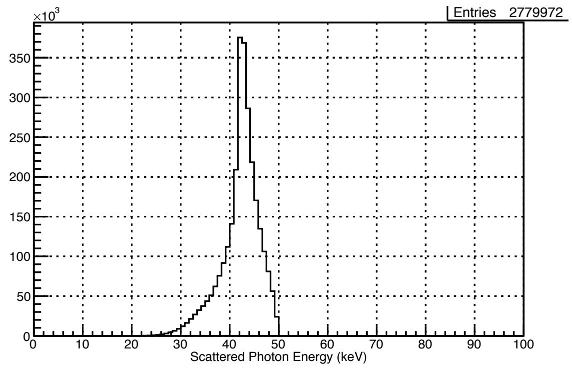

Figure 2. Spectrum of scattered photons for an incident photon energy of 50 keV.

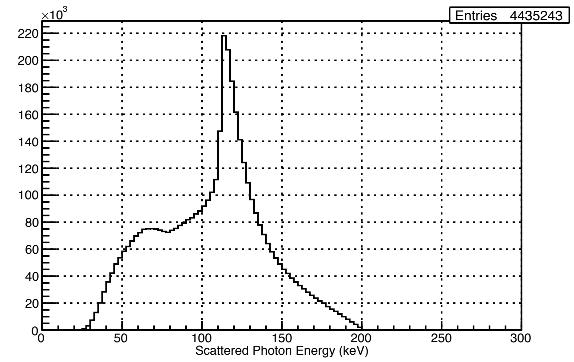

Figure 3. Spectrum of scattered photons for an incident photon energy of 200 keV.

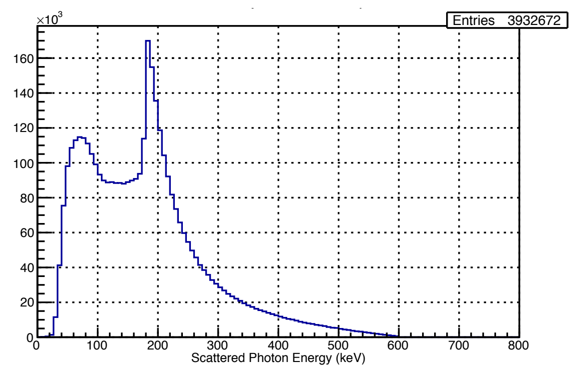

Figure 4. Spectrum of scattered photons for an incident photon energy of 600 keV.

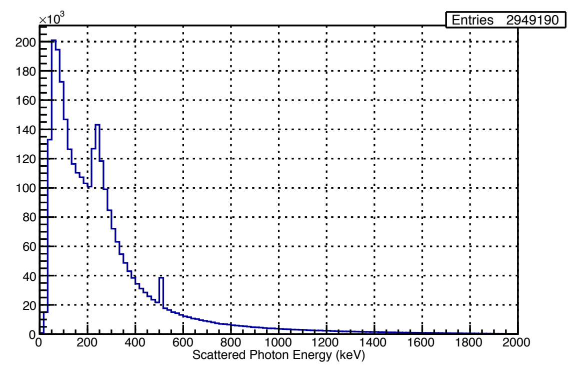

Figure 5. Spectrum of scattered photons for an incident photon energy of 2 MeV. Note the presence of the 511 keV line resulting from the onset of pair production.

Next Steps

We have now established a simulation of the atmospheric albedo flux using the GRESS simulation package. This alone represents a significant improvement with respect to the simulations that we had developed for the albedo polarimetry studies with BATSE.

The next step is to ascertain whether the polarization signature can be identified and measured using data from GBM. Fortunately, the GRESS package also includes a high-fidelity model of the Fermi GBM instrument and the surrounding spacecraft materials. GRESS can be used to simulate the response of GBM to incident flux of radiation. In this case, we would use the simulated atmospheric albedo to determine the GBM response to the scattered photon flux. The asymmetries in the angular distribution shown in Figures 6-11 would result in differences in GBM detector responses that would depend on various factors, including the orientation of the spacecraft with respect top the Earth. This should facilitate a determination of the ability for Fermi-GBM to extract polarization information for both gamma-ray bursts and solar flares.

The GRESS package represents a type of tool that was not available for BATSE. Leveraging off the development effort for GRESS offers the promise of more efficiently studying the GBM response to atmospheric albedo. We intend to continue our work in this area. For now, we are

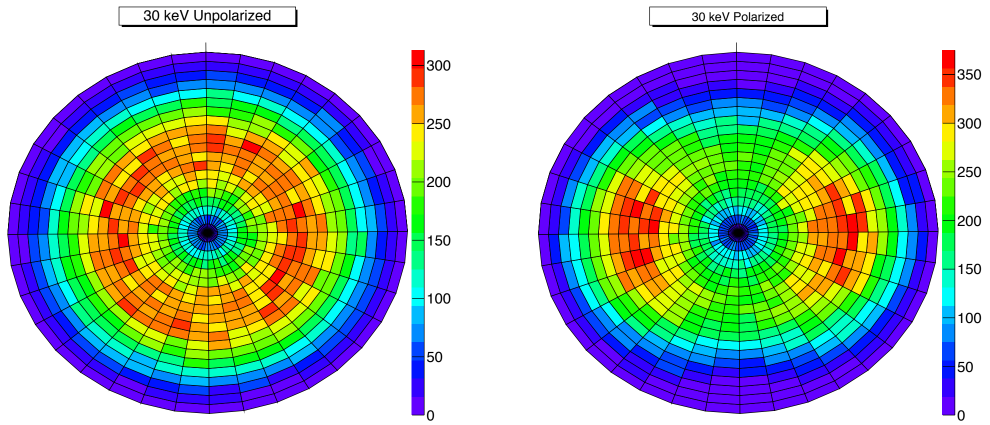

Figure 6. Angular distributions of the scattered photons for an incident mono-energetic beam of 30 keV. The unpolarized case is shown on the left. The polarized case is shown on the right.

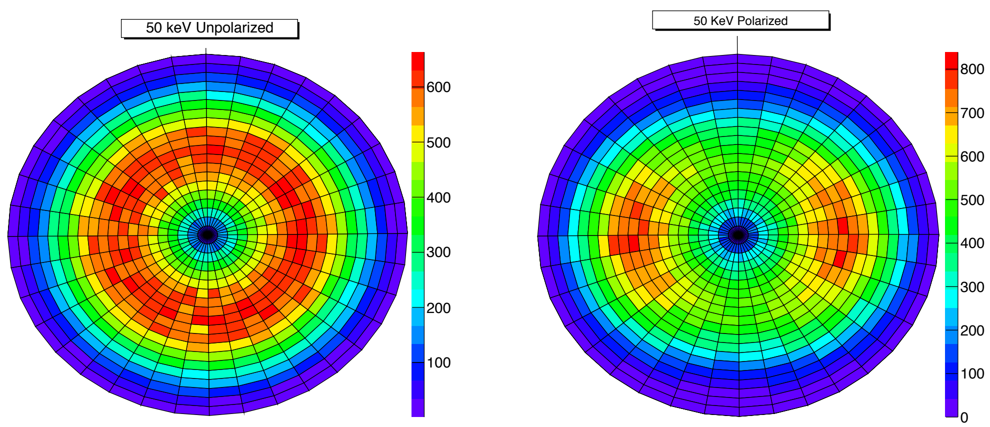

Figure 7. Angular distributions of the scattered photons for an incident mono-energetic beam of 50 keV. The unpolarized case is shown on the left. The polarized case is shown on the right.

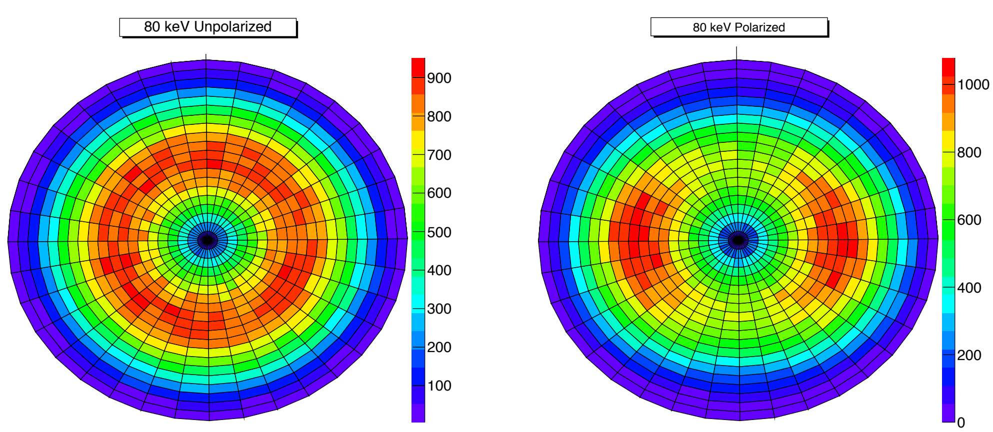

Figure 8. Angular distributions of the scattered photons for an incident mono-energetic beam of 80 keV. The unpolarized case is shown on the left. The polarized case is shown on the right.

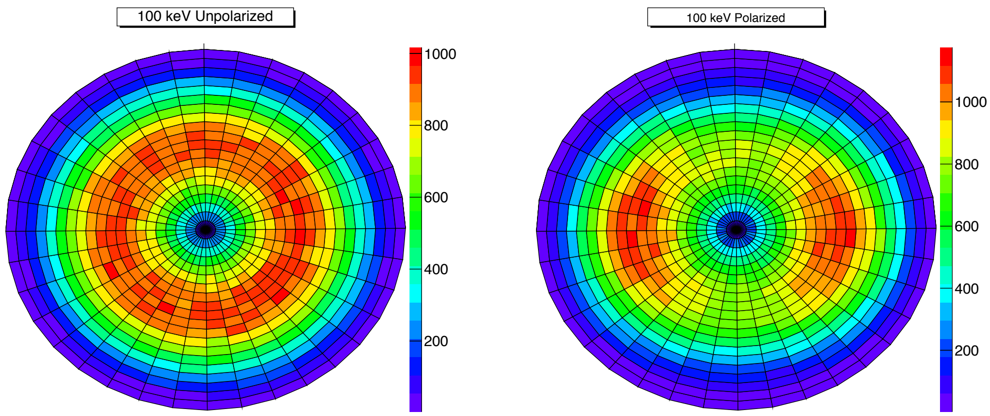

Figure 9. Angular distributions of the scattered photons for an incident mono-energetic beam of 100 keV. The unpolarized case is shown on the left. The polarized case is shown on the right.

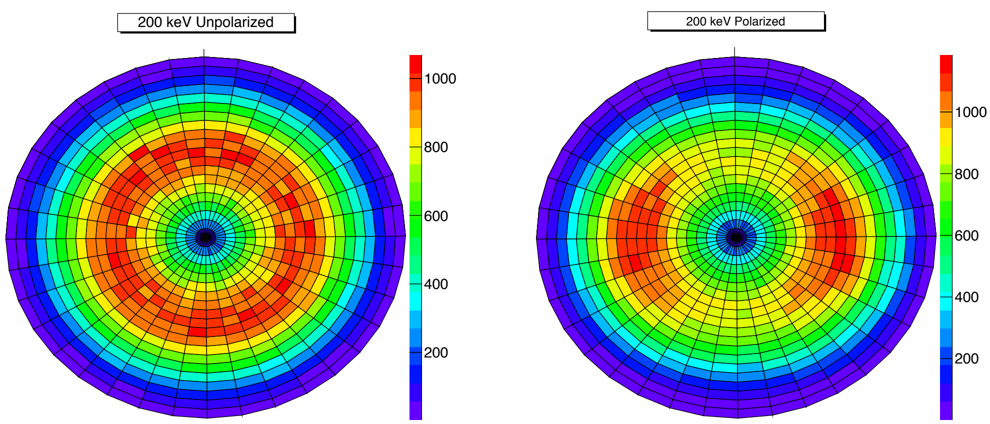

Figure 10. Angular distributions of the scattered photons for an incident mono-energetic beam of 200 keV. The unpolarized case is shown on the left. The polarized case is shown on the right.

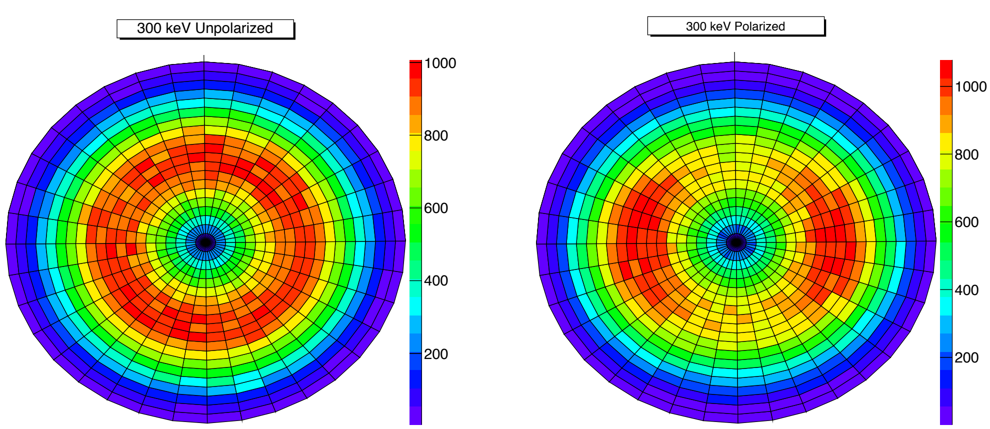

Figure 11. Angular distributions of the scattered photons for an incident mono-energetic beam of 300 keV. The unpolarized case is shown on the left. The polarized case is shown on the right.

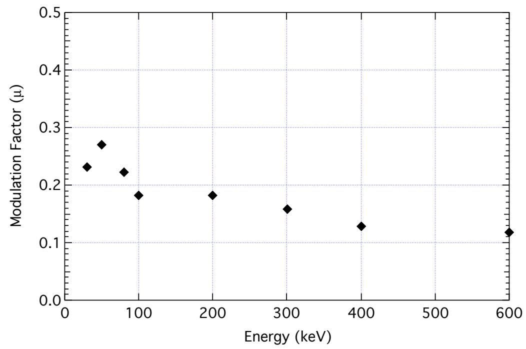

Figure 12. Estimated modulation factor as a function of incident photon energy. This is an attempt to parameterize the asymmetries in the angular distributions shown in Figures 6-11.

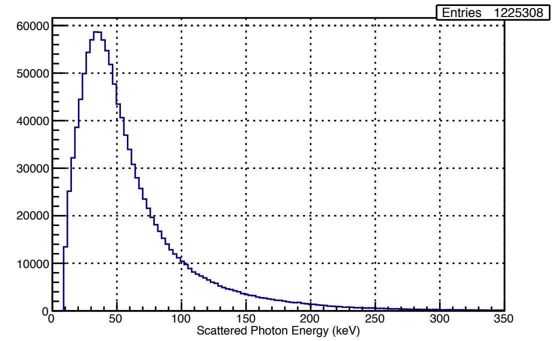

Figure 13. Energy spectrum of the scattered radiation for an incident $E^{-2.0}$ photon spectrum.

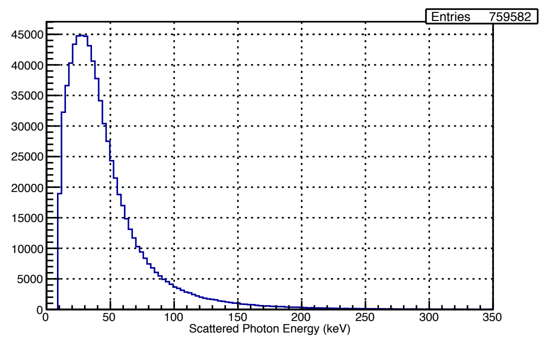

Figure 14. Energy spectrum of the scattered radiation for an incident $E^{-2.5}$ photon spectrum.

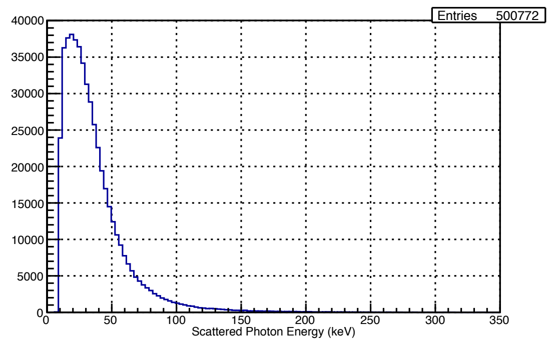

Figure 15. Energy spectrum of the scattered radiation for an incident $E^{-3.0}$ photon spectrum.

preparing a publication that describes the nature of the albedo flux, based on our GRESS simulations. The next step will be to work with the GBM team to generate the needed response information and perhaps to measure polarization with GBM.

References

Bai, T. and R. Ramaty (1978). ApJ 219: 705.

Bissaldi, E., et al. (2009). Experimental Astronomy, 24, 47–88.

Boggs, S. E., et al. (2006). ApJ 638: 1129.

Chanan, G., et al. (1988). Solar Physics 118: 309.

Coburn, W. and S. E. Boggs (2003). Nature 423: 415.

Fishman, G. J., et al. (1994). ApJS 92: 229.

Hoover, et al. (2008). AIP Conference Proceedings (Vol. 1000, pp. 565–568).

Kalemci, E., et al. (2007). ApJS 169: 75.

Kippen, R. M. (2004) New Astronomy Reviews, 48, 221.

Lazzati, D. (2006). New Journal of Physics 8: 131.

Leach, J. and V. Petrosian (1983). ApJ 269: 715.

McConnell, M. L., et al. (1996a). American Institute of Physics Conference Series 374, 368.

McConnell, M. L., et al. (1996b). American Institute of Physics Conference Series 384, 851.

McConnell, M. L., et al. (2002). Solar Physics 210, 125-142.

McConnell, M. L., et al. (2003a). Bulletin of the American Astronomical Society 34, 850.

McConnell, M. L., et al. (2003b). Proc. SPIEI 4843, 8.

McConnell, M. L.and R. M. Kippen (2004). Bulletin of the American Astronomical Society 36, 1206.

McGlynn, S., et al. (2007). A&A 466: 895.

Rutledge, R. E. and D. B. Fox (2004). Monthly Notices of the Royal Astronomical Society 350: 1288.

Suarez-Garcia, E., et al. (2006). SoPh 239: 149.

Toma, K. et al. (2009), ApJ. 698, 1042.

Waxman, E. (2003). Nature 423: 388.

Wigger, C., et al. (2004). ApJ 613: 1088.

Willis, D. R., et al. (2005). A&A 439: 245.

Zhitnik, I. A., et al. (2006). SoSyR 40: 93.

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14. ABSTRACT

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